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Aeronautical and Maritime Research Laboratory

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ABSTRACT

The tensile properties and tensile fracture behaviour of BIS 812 EMA and Q1N naval constructional steel weldments have been studied over a wide range of test temperatures utilizing plain and notched tensile specimens. Under certain conditions "star" fracture is the preferred fracture mode, rather than the usually observed cup-and-cone type fracture. The propensity for "star" fracture increases with decreasing temperature and the transition temperature for cup and cone to "star" fracture is reduced by notching. This paper describes the fracture surface features resulting from tensile tests and the conditions under which they occur in these materials.

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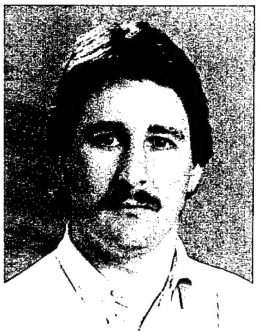
Executive Summary

The tensile properties and tensile fracture behaviour of BIS 812 EMA and Q1N naval constructional steel weldments have been studied over a wide range of temperatures utilizing plain and notched tensile specimens. Under certain conditions "star" fracture is the dominant fracture mode and the propensity for "star" fracture increases with decreasing temperature but decreases with the introduction of notches. This paper describes the fracture surface features resulting from tensile tests and the conditions under which they occur in these materials.

Authors



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Contents

1. Introduction

The fracture behaviour of notched and plain tensile specimens of parent plate BIS 812 EMA and Q1N naval construction steels have been examined [1]. These steels are used in ship and submarine hull construction, where fabrication of structures is generally accomplished by welding. In this work an assessment of the fracture behaviour of plain and notched tensile tensile specimens from the weld metal was undertaken. The temperature and specimen geometry used for the weld metal specimens were similar to those used in the assessment of the parent plate and, as such, will allow comparison with the tensile fracture behaviours of the parent plate materials.

The tensile behaviour of parent plate BIS 812 EMA and Q1N steels has shown the fracture process to be dependent on testing conditions such as temperature and the presence of pre-existing notches.

The change in fracture appearance in plain tensile specimens of BIS 812 EMA and Q1N parent plate from room temperature down to -100°C, is described schematically in Figure 1. At room temperature a region of fibrous fracture occurred at the centre of the specimen, but the size of this region diminished with decreasing temperature. "Star" fracture or radial cracking occurred over the entire temperature range with the most severe cracking occurring at the lowest temperature. On some occasions, the cracks traversed the specimen diameter and propagated along the axial direction, see Figure 2, to form longitudinal splits.

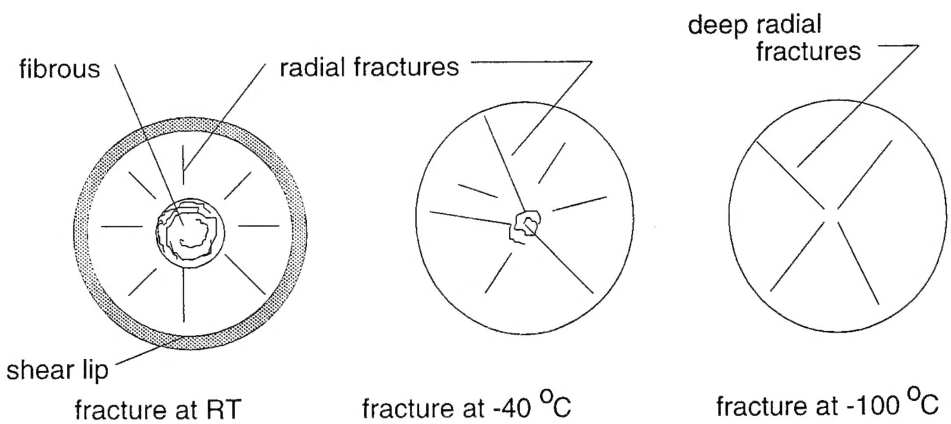


Figure 1: Fracture progression in plain tensile specimens, after Larson and Carr [2].

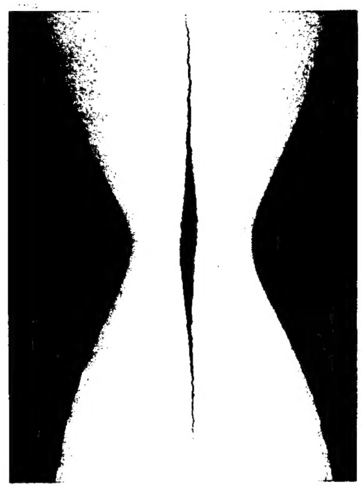


Figure 2: Longitudinal split in a BIS 812 EMA plain tensile specimen (parent plate, -105°C).

The notched tensile specimens also followed the fracture progression described by Larson and Carr [2], shown schematically in Figure 3. At room temperature, a large fibrous region and heavy shear lip developed, but as the temperature decreased the size of both the fibrous region and the shear lip reduced and a region of radial or "star" fracture in the mid section of the specimen developed. At lower temperatures deep radial cracks or longitudinal splits occurred, with the absence of fibrous areas and shear lips.

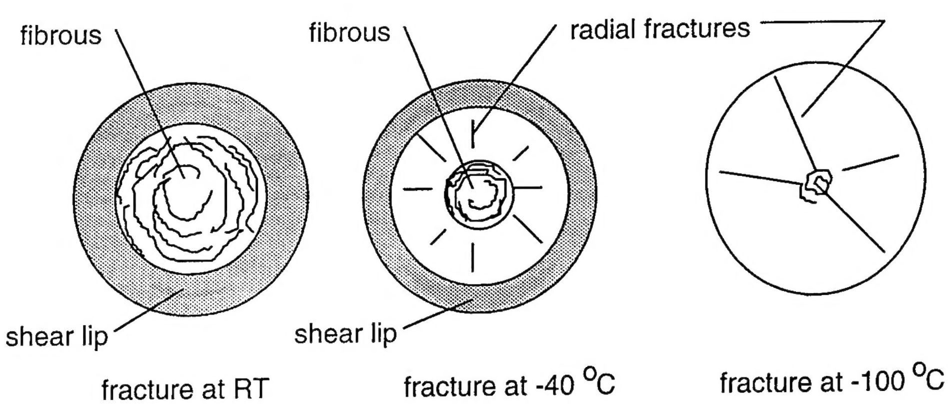


Figure 3: Fracture progression in notched tensile specimens, after Larson and Carr [2].

In all cases, the regions of fibrous fracture were composed of circumferential ridges emanating from the mid point of the specimen suggesting uniform circumferential crack growth from a nucleation point near the centre of the specimen.

Larson and Carr [2] have also classified the longitudinal fractures into Type 1 and Type 2 fractures, see Figure 4. From experimental evidence in earlier work [1] it seems reasonable to associate "star" fracture with the Type 2 fractures, also described by Shtremel et al [3], and longitudinal splitting with the Type 1 fractures.

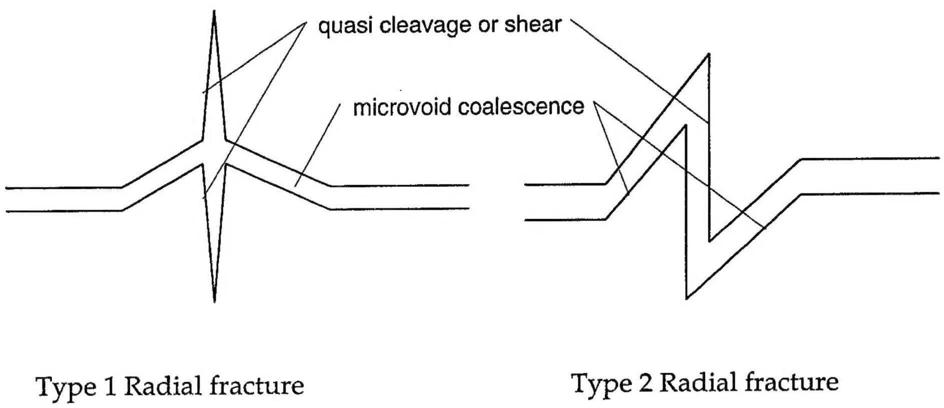


Figure 4: The two types of radial fracture, after Larson and Carr [2].

"Star" fracture and longitudinal splitting may be two distinct fracture processes. In examining the fracture surfaces of the parent plate material [1], the fracture mode progressed from fibrous, to radial cracking, to longitudinal splitting as the test temperature was reduced and/or notching increased. One fracture process dominates depending on the test conditions, as shown in Figures 1 and 3.

The formation of "star" fractures and longitudinal splits appear to be dependent upon the generation of the appropriate conditions within the central necked portion of the specimen. The process is suppressed, however, by the introduction of a notch and by increasing the testing temperature. "Star" fracture and longitudinal splitting do not appear to be associated with banding observed in these steels. The non-association with banding is reinforced by the observations that "star" fracture also occurs in transverse tensile specimens of BIS 812 EMA [4]. Fracture surfaces of specimens from the transverse orientation of BIS 812 EMA parent plate at room temperature consist of regions of fibrous fracture at the centre and "star" fracture away from the centre. The fracture surface is similar to that shown in Figure 1 as "fracture at -40^{o}C".

The "star" fracture observed in the BIS 812 EMA and the Q1N parent plate specimens is consistent with the mechanism of "star" fracture proposed by Zok and Embury [5] which is summarised thus, "the distribution of delamination events strongly suggest

that the planes of delamination depend upon events which occur during the test rather than being pre-existing planes of weakness due to prior processing". During work hardening, grain elongation and rotation occurs resulting in the alignment of grain boundaries. Grain boundaries contain void nucleating carbides and particles and during work hardening these particles produce voids that nucleate, elongate and grow on planes along the tensile axis. The formation of the neck introduces a triaxial stress state supplying the tangential and radial stresses [6] that act on these planes to facilitate "star" fracture. In the case of the BIS 812 EMA and the Q1N parent plate steels [1], the conditions for "star" fracture and longitudinal splitting appear to be extensive plastic deformation producing alignment of void nucleating particles, low temperatures and a triaxial stress state resulting in enhanced tangential and radial stresses.

Low temperatures cause a change in fracture mode from shear to quasi-cleavage. This transitional change is exhibited by both BIS 812 EMA and Q1N steels on the longitudinal fracture surfaces of the radial cracks which consist of elongated dimples at higher temperatures and quasi-cleavage at lower temperatures.

Shtremel' et al [3] claimed that, during straining, the initial fracture process was micro-cracking across the neck of the specimen. Where only limited necking occurs, the initial cracking leads to the failure of the specimen by either a fibrous or brittle fracture mode. The conditions for limited necking are achieved in notched tensile specimens. Where significant necking occurs and the fracture resistance is anisotropic, "star" fracture or longitudinal splitting occur. Anisotropic fracture resistance can be the result of processes such as temper embrittlement during heat treatment [3,5,7] and the alignment of fracture nucleating particles [5].

Longitudinal splitting, and "star" fracture do not necessarily represent a materials problem. The process occurs primarily because of the large tangential and radial stresses developed within the neck of tensile specimens and the high level of plastic deformation which creates regions of low crack resistance within the necked region.
This report describes the welding procedures, the orientation of the specimens with respect to the weld direction, the tensile properties and description of the fracture surfaces obtained over a range of temperatures and specimen geometry.

2. Materials

The tensile specimens used in this work were taken from coupons of welded BIS 812 EMA and Q1N, the chemical and mechanical properties of the parent plate materials have been published in references [8] and [9] respectively. BIS 812 EMA and Q1N parent plate steels have nominal room temperature yield strengths of 700 and 550 MPa respectively, both steels are quenched and tempered to produce fully martensitic microstructures. The coupon of BIS 812 EMA was supplied with a K-type weld preparation, welded according to specified welding procedure [10]. The Q1N was supplied as a double V preparation weld using the procedure detailed in [11].

Welding of the BIS 812 EMA steel was accomplished using the multipass method on a K-type weld preparation. The welding procedure consisted of a manual metal arc weld for the initial root pass and submerged arc welding for the subsequent fill and cap passes. The Q1N steel was welded using the synergic pulsed MIG (gas metal arc) process with an Ar-5% CO_2 shielding gas.

The weld preparations and specimen locations are illustrated in Figures 5(a) and (b). A total of four specimen types were tested: BIS 812 EMA weld metal, plain and notched and Q1N weld metal, plain and notched. The tensile specimen geometry and dimensions are shown in Figure 6(a) and the notch profile and placement in Figure 6(b).

Tensile tests were carried out on notched and plain specimens from the weld metal regions of both BIS 812 EMA and Q1N at the following nominal temperatures, +20, -20, -60 and -100°C. Three notched and three plain specimens of each material were tested at the above temperatures. After fracture, a specimen from each temperature/geometry combination was examined under the scanning electron microscope (SEM) to assess any change in fracture behaviour with change in temperature and/or presence of a notch.

3. Experimental Results

3.1 Tension Test Results

The material property data, determined from tensile tests in this work are not of significant importance as the work was primarily directed at a study of the events occurring at fracture, but for completeness the results are presented. For these tests, extensometers were not used and yield strengths for materials that did not exhibit a sharp yield point were not determined. Plain specimens from Q1N weld metal produced sharp yield points, whereas plain specimens of BIS 812 EMA weld metal did not.

The results of tensile tests on plain BIS 812 EMA and Q1N weld metal specimens are given in Table 1 and notched BIS 812 EMA and Q1N weld metal specimens in Table 2. Results are limited to ultimate tensile stress, fracture stress and reduction of area for BIS 812 EMA and yield stress, ultimate tensile stress, fracture stress and reduction of area for Q1N plain tensile specimens. Ductility measurements were restricted to reduction of area values as elongation measurements were influenced by the proximity of the weld metal to the parent plate. For the notched specimens ultimate tensile strength, fracture strength and reduction of area are reported.

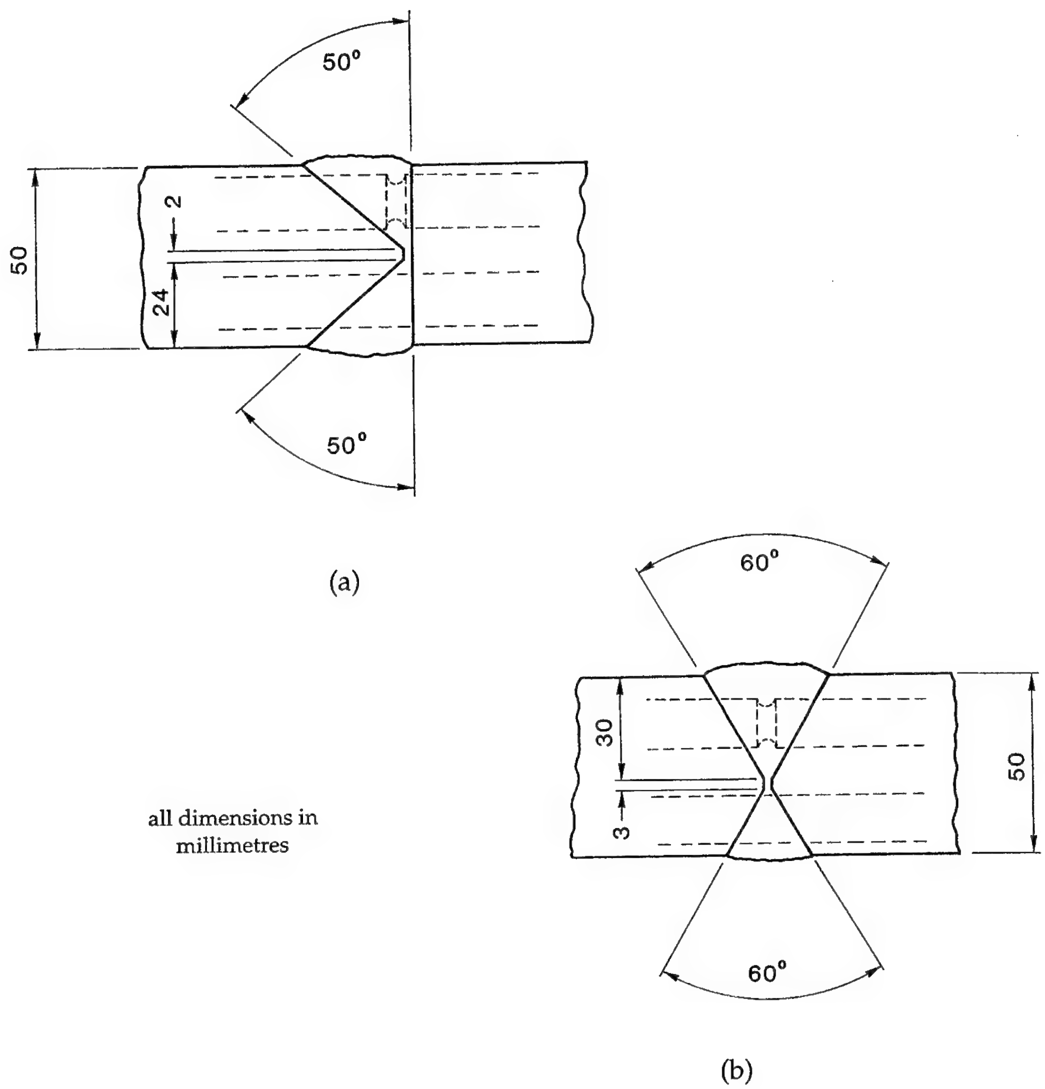


Figure 5: Weld preparation and specimen location with respect to the weld/plate orientation for (a) BIS 812 EMA and (b) Q1N.

The initial room temperature test on a welded BIS 812 EMA plain specimen resulted in necking and fracture in the parent plate region adjacent to the weld metal, indicating that the weld metal had a yield strength greater than the parent material.

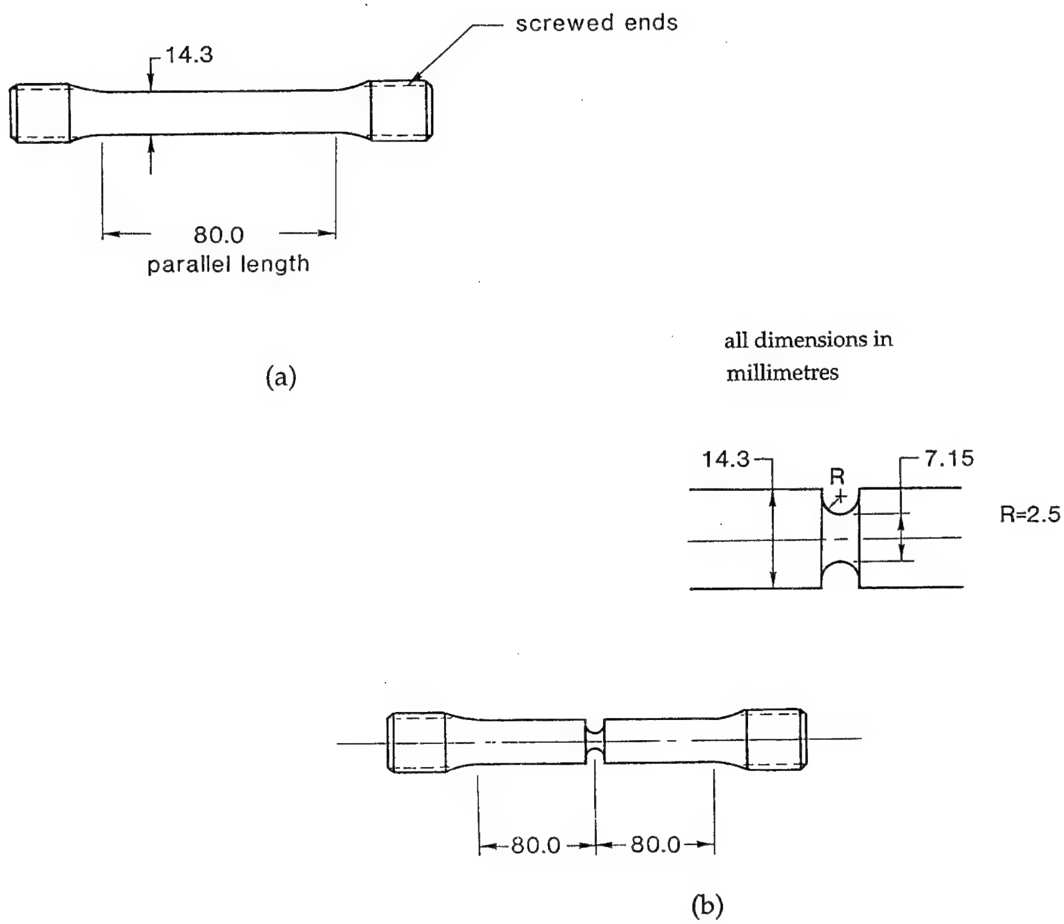


Figure 6: (a) the geometry of the smooth tensile specimen and (b) notch placement and profile.

The remainder of the plain BIS 812 EMA weld metal specimens were reduced in diameter from a nominal 14.3 mm to a nominal 10.135mm and the parallel length reduced to 10.0 mm to keep it within the weld metal region restricting elongation and fracture to the weld metal.

Table 1: Results of tensile tests on plain BIS 812 EMA and Q1N weld metal tensile specimens (specimens marked 'not measured' were used in SEM examination).

Material	Temp. ^oC	Yield Stress	Ultimate Tensile Stress (nominal)	Fracture Stress (true)	Reduction of Area %
BIS 812 EMA	21	(specimen failed outside the weld metal region)			
BIS 812 EMA	21		816	1614	68
BIS 812 EMA	21		817	-	not measured
BIS 812 EMA	-20		870	1653	66
BIS 812 EMA	-21		857	1665	67
BIS 812 EMA	-20		853	-	not measured
BIS 812 EMA	-62		888	1709	64
BIS 812 EMA	-63		903	1814	69
BIS 812 EMA	-62		902	-	not measured
BIS 812 EMA	-96		948	1860	67
BIS 812 EMA	-103		962	1859	67
BIS 812 EMA	-102		958	-	not measured
Q1N	21	615	699	1296	63
Q1N	21	613	707	1333	65
Q1N	21	612	708	-	not measured
Q1N	-23	643	742	1331	61
Q1N	-20	639	742	1371	64
Q1N	-22	641	738	1353	63
Q1N	-59	668	778	-	not measured
Q1N	-60	668	770	-	not measured
Q1N	-61	672	773	1433	62
Q1N	-104	716	819	1451	59
Q1N	-104	717	814	-	not measured
Q1N	-103	714	813	-	not measured

Table 2: Results of tests on notched BIS 812 EMA and Q1N weld metal tensile specimens (specimens marked 'not measured' were used in SEM examination)

Material	Temp. ^oC	UTS (nominal)	Fracture Stress (true)	Reduction of Area %
BIS 812 EMA	21	1132		not measured
BIS 812 EMA	21	1134	1688	40
BIS 812 EMA	21	1132	1701	42
BIS 812 EMA	-23	1202	-	not measured
BIS 812 EMA	-27	1212	1750	39
BIS 812 EMA	-23	1198	1769	40
BIS 812 EMA	-57	1241	-	not measured
BIS 812 EMA	-61	1254	1814	38
BIS 812 EMA	-63	1257	1702	37
BIS 812 EMA	-107	1340	-	not measured
BIS 812 EMA	-102	1320	1779	35
BIS 812 EMA	-102	1314	1787	35
Q1N	21	1088	-	not measured
Q1N	21	1061	1482	36
Q1N	21	1066	1435	33
Q1N	-18	1103	-	not measured
Q1N	-19	1128	1561	33
Q1N	-18	1106	1518	32
Q1N	-59	1175	-	not measured
Q1N	-64	1155	1618	35
Q1N	-57	1141	1528	33
Q1N	-104	1212	-	not measured
Q1N	-107	1239	1575	30
Q1N	-104	1234	1526	25

3.2 Scanning Electron Microscopy

Photographs taken in the scanning electron microscope of the fracture surfaces of notched and plain BIS 812 EMA weld metal tensile specimens appear in Figure 7 and notched and plain Q1N weld metal tensile specimens in Figure 8.

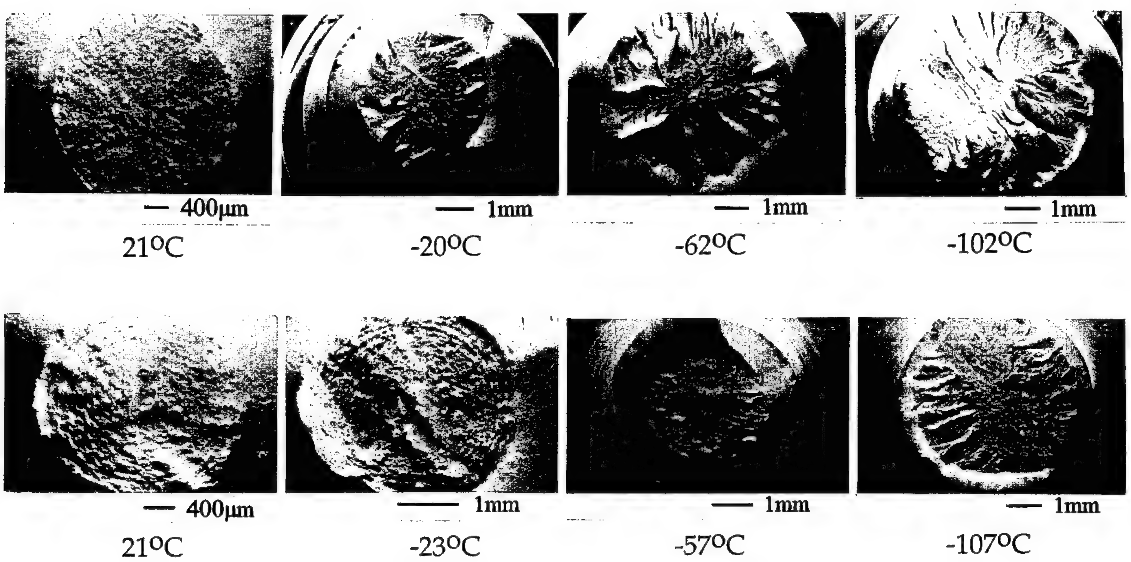


Figure 7: Fracture appearance of BIS 812 EMA weld metal tensile specimens, plain (upper) and notched (lower).

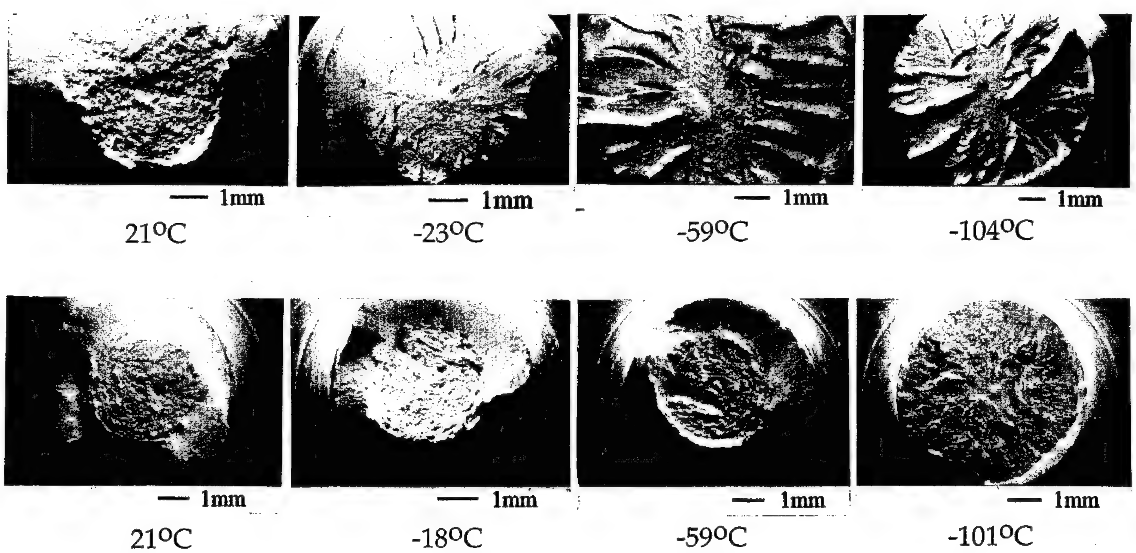


Figure 8: Fracture appearance of Q1N weld metal tensile specimens, plain (upper) and notched (lower).

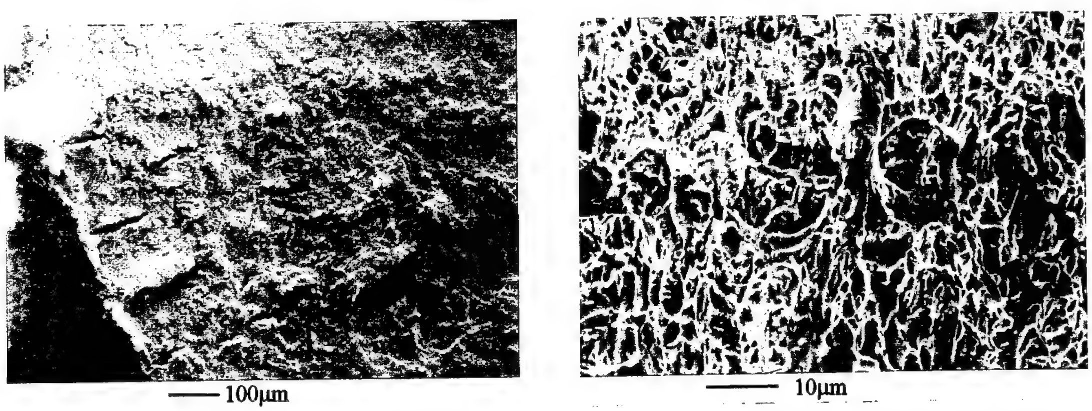
3.3 SEM Fracture Face Descriptions

Described below are the fracture surfaces of plain and notched tensile specimens of BIS 812 EMA and Q1N weldments as viewed in the scanning electron microscope.

3.3.1 BIS 812 EMA Weld Metal, Plain Tensiles

At room temperature the surface consists of fibrous fracture at the centre and shear lip failure at the edge of the specimen. Some small radial cracks are present in the fibrous region, see Figure 9(a), more severe cracks appear closer to the outer diameter of the specimen. The fibrous fracture consists entirely of equi-axed dimples.

At -20°C, radial cracks have developed and the shear lip is still present. The central fibrous region consists of equi-axed dimples and elongated dimples on the longitudinal faces of the radial cracks, see Figure 9(b). As the temperature reduces (-62°C and -102°C) the radial cracking in the central region becomes deeper, extending further toward the centre of the specimen and the shear lip is not formed.



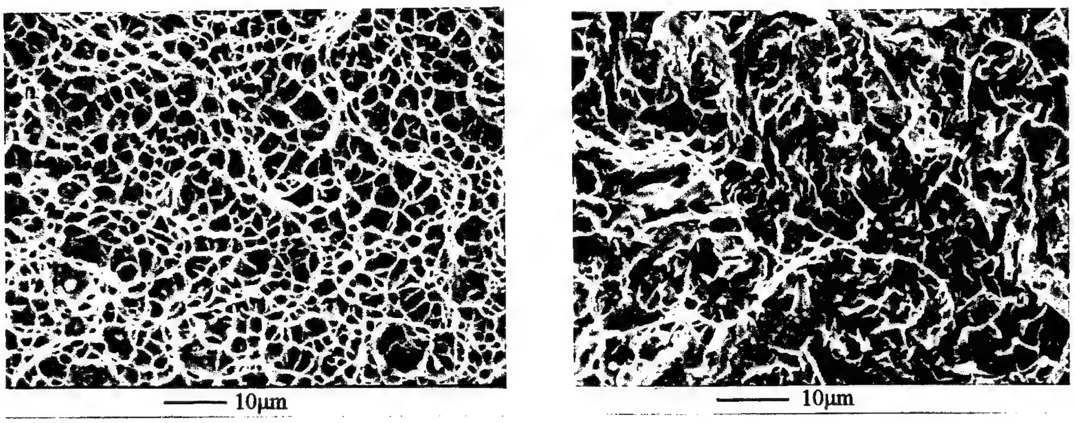
(a) (b)

Figure 9: Scanning electron microscopy of BIS 812 EMA weld metal, plain tensile specimens (a) radial cracks in the fibrous region, 21°C and (b) elongated dimples on the radial crack face, -20°C.

3.3.2 BIS 812 EMA Weld Metal, Notched Tensiles

The fracture surface appearance at both 21°C and -23°C appear similar (even though the magnifications are different), fibrous fracture at the centre and a shear lip at the edge with no radial cracking evident within the fibrous region. The diameter of the fibrous region decreasing as the temperature drops from 21°C to -23°C. The fracture

surfaces on both of these samples comprise equi-axed dimples, see Figure 10(a). At lower temperatures, -57°C and -107°C, radial cracks are present, although they are not as severe as with the plain BIS 812 EMA weld metal specimens at the same temperatures. The longitudinal face of the radial fracture at -107°C shows quasi-cleavage, Figure 10(b).



(a) (b)

Figure 10: Scanning electron microcopy of BIS 812 EMA weld metal, plain tensile specimens, (a) equi-axed dimples in the fibrous region, 21°C and (b) longitudinal face of radial fracture showing quasi-cleavage, -107°C

3.3.3 Q1N Weld Metal, Plain Tensiles

At room temperature, the surface consists of fibrous fracture and a shear lip with minor radial cracking evident, see Figure 11(a). The region of fibrous fracture comprises equi-axed dimples.

As the temperature decreases the fracture appearance alters, at -23°C, radial cracking is evident between the central fibrous region and the shear lip. The fibrous region consists of equi-axed dimples but the longitudinal faces of the radial cracks show a combination of elongated dimples and quasi cleavage.

At -59°C and -104°C, there is an increase in radial cracking, although the pattern of the cracks is not radially symmetrical. The radial cracks increase in severity as the temperature decreases although the number appears to pass through a maximum at -59°C. The longitudinal fracture face on the radial cracks at -59°C and -104°C show signs of quasi-cleavage, see Figure 11(b).

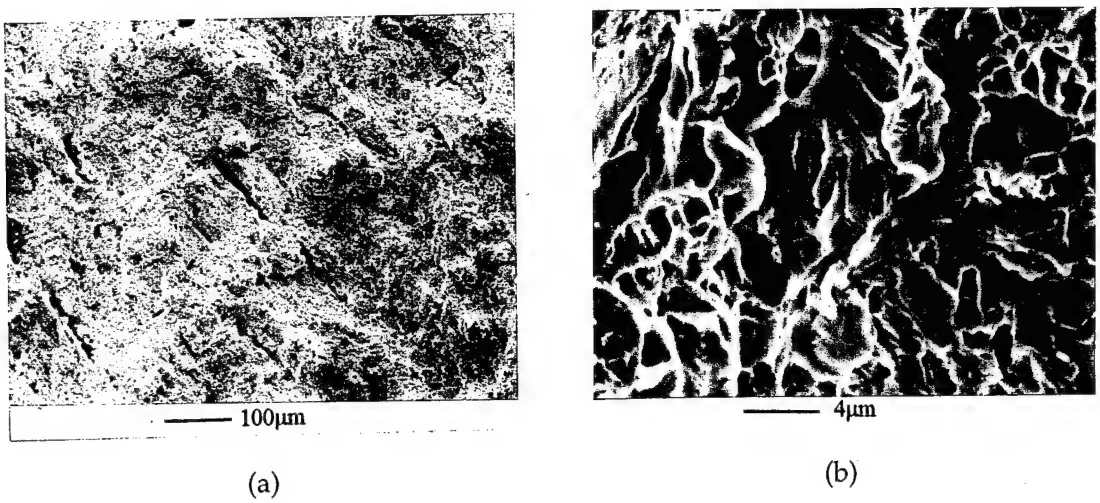


Figure 11: Scanning electron microscopy of Q1N weld metal, notched tensile specimens (a) Radial cracking in the fibrous region, 21°C, and (b) Quasi-cleavage on a radial crack, -104°C.

3.3.4 Q1N Weld Metal, Notched Tensiles

The fracture surfaces on the notched Q1N weld metal specimens at 21°C, -18°C and -59°C were fibrous with shear lips but without any radial cracking. The fracture surfaces consisted entirely of equi-axed dimples, see Figure 12(a). At -101°C the fracture appearance was quasi-cleavage with some evidence of grain boundary separation, see Figure 12(b). The fracture surface of this particular specimen/geometry/temperature combination was devoid of any radial cracks or longitudinal splits that might have been expected at this temperature.

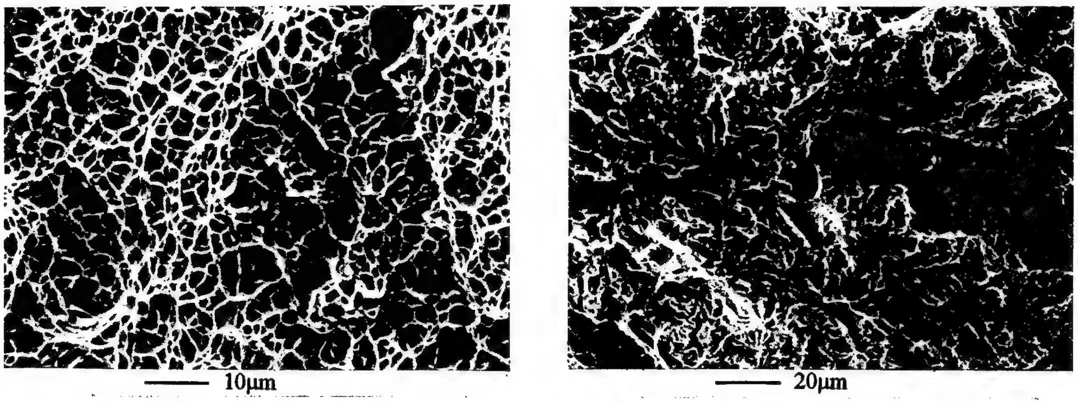


Figure 12: Scanning electron microscopy of Q1N weld metal, notched tensile specimens (a) equi-axed dimples in the fibrous region, 21°C and (b) brittle square fracture showing quasi-cleavage, -101°C.

4. Discussion

The tensile properties of the BIS 812 EMA and Q1N weldments show an increase in UTS and fracture strength and a reduction in ductility as the temperature decreases. The Q1N weld metal plain tensile specimens exhibited a definite yield point (upper/lower yield point with yield point elongation) whereas the BIS 812 EMA weld metal plain specimens reached the elastic limit and work hardened without a definite yield point or yield point elongation.

The behaviour of plain and notched BIS 812 EMA and Q1N weld metal tensile specimens is similar to the behaviour observed during tensile testing of the parent plate steels [1]. The weld metal specimens from both materials exhibit "star" fracture behaviour and the "star" fracture is suppressed by the introduction of a notch and by increasing the testing temperature.

At room temperature, small radial cracks are present on the fracture surface of both BIS 812 EMA and Q1N weld metal plain tensile specimens and these develop into more severe "star" fracture at lower temperatures. Over the entire temperature range the appearance of the "star" or radial fracture is similar for both the BIS 812 EMA and Q1N weldments tested at the same temperature.

The notched samples show suppression of "star" fracture behaviour, BIS 812 EMA notched tensile specimens show "star" fracture behaviour does not occur until the temperature falls to -60°C while it is completely suppressed for notched Q1N weld

metal specimens (ie. for plain Q1N weld metal tensile specimens, some radial cracking is present at room temperature but not in the notched weld metal specimens). As the temperature decreases from room temperature, the failure mode changes from "cup and cone" or fibrous fracture/shear lip to "star" fracture type behaviour similar to the type of behaviour exhibited by the parent plate material [1]. This behavioural trend (not necessarily at the same transition temperature) also occurred for BIS 812 EMA plain and notched tensile specimens but not for the Q1N notched specimens.

For the Q1N notched specimens, "cup and cone" behaviour occurs from room temperature down to -60°C but at -100°C fracture was by quasi-cleavage without evidence of "star" fracture/radial cracking. The crack growth in the neck of Q1N notched weld metal tensile specimens at higher temperatures is by void coalescence, but the combination of decreasing toughness and increasing load together with insufficient deformation favours unstable cleavage crack propagation instead of "star" fracture.

An interesting feature of the fracture surfaces of the weldments of both BIS 812 EMA and Q1N is that the radial or "star " cracking does not necessarily follow a true radial pattern. In some specimens, BIS 812 EMA, smooth tensile at -102°C and Q1N, smooth tensile at -59°C seen in Figures 7 and 8, the "star" cracks tend to follow a directional pattern. This effect was not seen in the parent plate specimens [1] and may be due to the non-uniform microstructure of the weldments.

The progressive nature of "star" fracture production with reduction in temperature in the weld metal closely follows that produced in parent plate specimens [1]. Figures 13 and 14 show the fracture surfaces of BIS 812 EMA and Q1N parent plate plain and notched tensile specimens for comparison with weld metal samples. The obvious difference in fracture appearance between weld metal and parent plate specimens is that for the weld metal specimens, "star" fracture does not become prominent until much lower temperatures are reached. For BIS 812 EMA parent plate plain tensile specimens, "star" fracture and longitudinal splitting are present at room temperature but for the plain weld metal specimens, only small radial cracks are present. At -100°C, the parent plate specimen has produced a longitudinal split, while the weld metal specimen resulted in a "star" fracture. For the BIS 812 EMA notched tensiles, "star" fracture is suppressed for both parent plate and weld metal samples for temperatures down to -20°C. Below this temperature "star" fracture production is not as prominent in the weld metal as can be seen from Figure 7, but for the parent plate the transition is from "star fracture" at -80°C to longitudinal splitting at -100°C. A similar trend is observed for plain Q1N parent plate and weld metal specimens. At -100°C the fracture surface of the plain weld metal specimen does not match the severity (depth) of cracks on the surface of the plain parent plate specimen at room temperature. As already noted "star" fracture/longitudinal splitting is completely suppressed for the notched Q1N weld metal specimens, "cup and cone" failure occurs at temperatures down to -80°C and the mode of fracture at -100°C is a flat cleavage fracture, not "star" fracture.

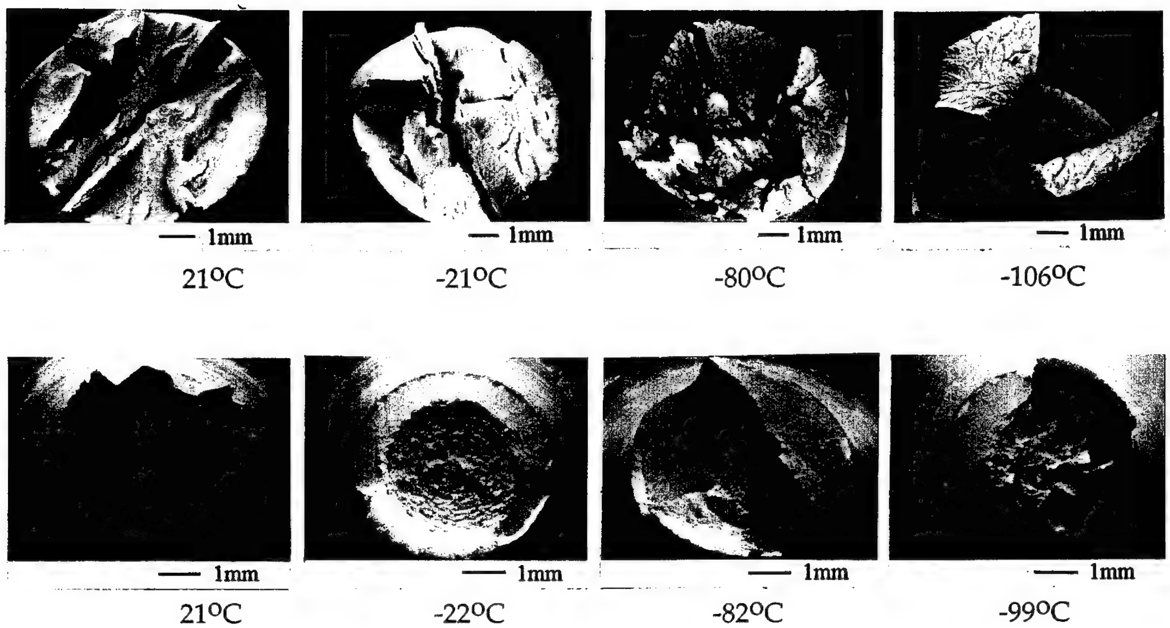


Figure 13: Fracture appearance of BIS 812 EMA parent plate tensile specimens, plain (upper) and notched (lower).

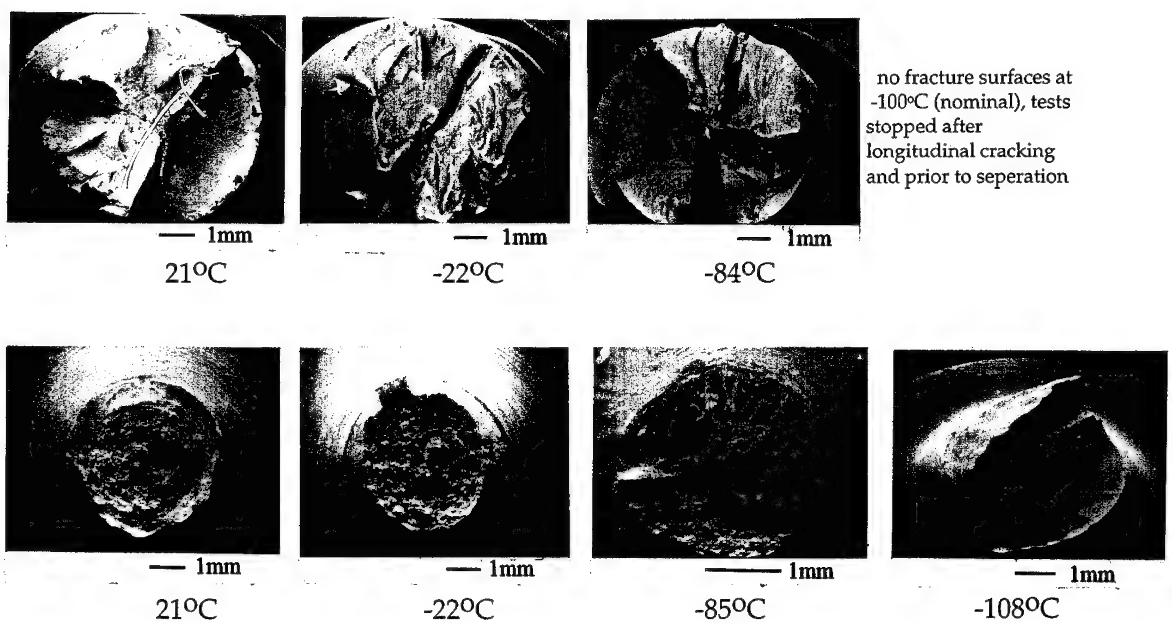


Figure 14: Fracture appearance of Q1N parent plate tensile specimens, plain (upper) and notched (lower).

Circumferential crack growth or fibrous fracture is prevalent at a lower sub-zero temperature for weld metal specimens compared with parent plate specimens. At room temperature some microcracking is evident in the fibrous region in both weld metal materials (BIS 812 EMA and Q1N), this cracking terminates abruptly resulting in very short crack lengths. This behaviour is consistent with the weld metal region being susceptible to crack initiation due to weld defects or a low toughness region of the microstructure but also consistent with an observed increase in dynamic fracture toughness over that of parent plate [8].

Following Zok and Embury [5] a possible mechanism for star fracture from scanning electron microscopy observations is summarised as follows, radial cracking occurs due to alignment of void nucleating particles, the stress distribution in the neck of the material [13] and weld metal susceptibility to crack initiation. At higher (room) temperatures the cracks terminate while still quite small, see Figures 9(a) and 11(a), while at lower temperatures the cracks propagate inward toward the centre of the sample and outward towards the edge as well as in the longitudinal direction. As the temperature drops the fracture resistance also drops [8] resulting in deeper, longer cracks.

At some temperatures (eg. notched BIS 812 EMA at -57°C) a shear lip region is present along with "star" fracture. This phenomenon can be explained as a function of the fracture toughness. At this temperature, crack propagation continues until the toughness of the material is greater than the stress intensity factor at the crack tip. The stress state is also lower at the outer part of the neck thus reducing the stress intensity at the tip of the crack. When temperatures are higher than -57°C, the higher dynamic fracture toughness plays a role in limiting the radial cracking. At lower temperatures the toughness of the material is low enough to allow the radial cracks to propagate to the edge and centre of the sample and failure of the sample is by quasi cleavage, without shear lip formation.

Notched weld metal specimens show suppression of "star" fracture. Zok and Embury [5] proposed the alignment of crack nucleation particles responsible for conditions favourable to "star" fracture but without the plastic deformation allowed by plain tensile specimens, notched tensiles cannot produce the microstructure conducive to "star " fracture. Low temperatures are required to achieve a significant reduction in fracture toughness to promote crack initiation and growth for "star " fracture [1].

5. Conclusions

The tensile fracture behaviour of BIS 812 EMA and Q1N weld metal over the temperature range of 21°C to -100°C is similar to that observed for parent plate materials over the same temperature range.

The resulting fracture surfaces do not mirror the fracture surfaces of the parent plate. For BIS 812 EMA weld metal specimens there appears to be a temperature offset separating the fracture faces produced with plain and notched specimens. Results from tensile tests on Q1N weld metal specimens show a change in fracture mechanism, for plain specimens "star" fracture follows fibrous fracture as the temperature is reduced. Cleavage fracture follows the fibrous fracture for the notched specimens

The results are interesting aspects of tensile fracture but are of limited interest with respect to failure mechanisms as they occur after appreciable plastic deformation and out of load design limits of the material.

The combination of stress state, plastic deformation and fracture toughness will determine the type of fracture surface produced in a tensile specimen.

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The tensile fracture behaviour of the weld metal of BIS 812 EMA and Q1N naval construction steels

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ABSTRACT

The tensile properties and tensile fracture behaviour of BIS 812 EMA and Q1N naval constructional steel weldments have been studied over a wide range of test temperatures utilizing plain and notched tensile specimens. Under certain conditions "star" fracture is the preferred fracture mode, rather than the usually observed cup-and-cone type fracture. The propensity for "star fracture" increases with decreasing temperature and the transition temperature for cup and cone to "star" fracture is reduced by notching. This paper describes the fracture surface features resulting from tensile tests and the conditions under which they occur in these materials.